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By Mission Operations Section
TRW Systems Group

MSC Task Monitor
A.N. Lunde

MISSION PLANNING AND ANALYSIS DIVISON

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PROJECT APOLLO

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NOMENCLATURE

AAP	Apollo Applications Program
AORA	Atlantic Ocean recovery area
CM	command module
COI	contingency orbit insertion
CSM	command service module
ΔV	incremental change in velocity
FPR	flight propellant reserve
fps	feet per second
g	unit of gravitational acceleration
g. e. t.	ground elapsed time
h_p	perigee altitude
IGM	iterative guidance mode
IORA	Indian Ocean recovery area
LET	launch escape tower
L/D	lift-to-drag ratio
RCS	reaction control system
SCS	stabilization and control system
SM	service module
SPS	service propulsion system
t_B	burn time

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1. SUMMARY AND INTRODUCTION

Feasibility studies are currently underway within the Manned Spacecraft Center (MSC) to assess the overall effectiveness of two specific launch-to-orbit insertion methods for the first Apollo application mission. These methods include (1) a two stage to orbit insertion using an uprated Saturn I configuration, with insertion being achieved by the second stage S-IVB booster, and (2) a two and one-half stage to orbit insertion using the uprated Saturn I configuration, with insertion being achieved by the service propulsion system (SPS) thruster. The launch phase abort study is directed specifically at the two stage to orbit portion of the feasibility study. The launch vehicle trajectory used for this study was taken from the Reference, and the associated weight statement and propellant allowables were supplied by the Mission Planning and Analysis Division (MPAD).

The purpose of this study was to determine the launch abort and contingency orbit insertion capabilities available for the previously mentioned launch to orbit insertion system. Specifically, three time dependent questions were asked by MPAD and answered in this document: (1) what is the length of time during which a Mode IV (contingency orbit insertion) could be performed; (2) what is the length of time during which a Mode III abort (to the Atlantic Ocean) could be performed; and (3) what period of time, if any, is it necessary to overfly Africa?

In summary, for aborts occurring along the nominal trajectory, the results reflect the following: (1) the time during which a contingency orbit insertion (COI) can be performed occurs between the ground elapsed times of 10 minutes and 1.5 seconds and 10 minutes and 12.6 seconds; (2) the time during which a Mode III abort can be accomplished occurs between the ground elapsed times of 10 minutes and 1.4 seconds and 10 minutes and 14.4 seconds; and (3) assuming no malfunctions associated with the abort maneuvering capability, there exists continuous overlapping coverage to avoid the continent of Africa by either retrograde (Mode III) or posigrade (Mode IIIA) thrusting to ensure landings in the Atlantic or the Indian Ocean recovery areas. If a malfunction did occur, where SPS thrusting capability did not exist, land landings would occur during the period extending from ground elapsed times of 10 minutes and 1.1 seconds to 10 minutes and 11.7 seconds.

2. INPUT DATA

The launch trajectory used for this study was derived from the Reference. For the purpose of simulation, the launch to insertion parameters from launch escape tower (LET) jettison to insertion conditions (81/120-nautical mile perigee altitude/apogee altitude orbit) were generated using a precision integration program implementing the iterative guidance mode (IGM) for launch vehicle guidance.

Nominal launch vehicle data obtained from the Reference are tabulated in Table I. Spacecraft propulsion, weight, and aerodynamic characteristics were provided by MPAD and are tabulated in Table II.

3. ABORT MODE PROCEDURES

The method by which the spacecraft and crew recover from an in-flight failure during the launch to insertion mission phase depends primarily on trajectory conditions at the point of failure. The basic modes of spacecraft launch aborts are (1) return to earth and (2) contingency orbit insertion. When there is overlapping coverage by these two methods, certain criteria such as a time critical situation would be used to decide the more feasible approach. The following is a brief description of the launch abort modes (excluding Mode I, which was not a part of the analysis) designated for the AAP-1 Mission.

> <u>Mode II</u> - Aborts of this type consist of the spacecraft separating from the launch vehicle and flying a free-fall, full-lift (bank angle equals zero degrees) entry to an Atlantic Ocean landing. The Mode II region begins at LET jettison and continues to the point where the Mode II maneuver sequence results in a landing 3200 nautical miles downrange from the launch pad.
>
> <u>Mode III</u> - This recovery procedure involves a retrograde attitude service propulsion system (SPS) variable burn up to a maximum incremental velocity (ΔV) of 1000 feet per second. SPS ignition occurs 125 seconds after the abort signal. This delay time is required for separation from the launch vehicle and orientation to the desired ignition attitude. A full-lift entry (bank angle equals zero degrees) is flown to a point where 0.2-g acceleration is sensed. At that point, the remaining portion of the entry procedure is flown at a bank angle of 55 degrees (south). Mode III begins at the Mode II 3200-nautical mile landing point and ends when the SPS ΔV available is not large enough to maintain the landing point at 3200 nautical miles.
>
> <u>Mode IIIA</u> - This abort procedure involves varying SPS ΔV up to the maximum available (1000 feet per second) in a posigrade attitude in order to achieve an Indian Ocean landing at 8200 nautical miles downrange. Atmospheric entry is flown at a bank angle of 60 degrees (half lift). This abort procedure was included as a backup mode to the Mode III retrograde abort procedure to the Atlantic Ocean recovery area. Normally this procedure is avoided if possible due to the sensitivity of the flight-path angle and velocity when attempting a return-to-earth posigrade attitude abort.

Mode IV - The abort to COI procedure is used to insert the spacecraft into an orbit having a perigee altitude of at least 75 nautical miles. Deorbit capability from any point in the contingency orbit must be considered when designating the Mode IV abort regime. The maneuver itself employs the SPS in the posigrade burn attitude to supply the necessary velocity increment to place the spacecraft into the desired orbit.

The posigrade and retrograde spacecraft attitudes used for the SPS abort burn maneuver are shown in Figure 1. The sequence of events for the launch abort simulations used in this study is presented in Table III.

4. RESULTS AND CONCLUSIONS

The results of the AAP-1 two stage to orbit trajectory analysis in the Mode III and Mode IV region are presented in Figures 2 through 9. In the Mode III region, only aborts from the nominal trajectory were considered. The Mode IV analysis, however, includes aborts from the nominal as well as off-nominal launch trajectories.

Shown in Figures 2 and 3 are plots of the nominal AAP-1 trajectory. Figure 2 shows nominal flight-path angle and velocity plotted as a function of ground elapsed time from lift-off. Figure 3 illustrates altitude and range as a function of ground elapsed time. The plots begin at S-IVB ignition and continue to insertion. The justification for beginning the plots at S-IVB ignition is that tower jettison, and thus the beginning of Mode II, occurs after the ignition of the S-IVB stage. The Mode III and Mode IV abort regions do not begin until a point very near insertion.

The first time at which a Mode III retrograde abort would occur on the nominal trajectory is at a ground elapsed time of 10 minutes and 1.1 seconds. Figure 4 shows the amount of ΔV required to perform a Mode III retrograde maneuver to the Atlantic Ocean recovery area. The required ΔV is plotted as a function of ground elapsed time. The required ΔV is plotted on the left-hand vertical axis, and the corresponding SPS burn time is plotted on the right-hand vertical axis. Two values of lift-to-drag ratios were assumed for the Mode III aborts: 0.28 and 0.229. The results of using both lift-to-drag ratios are shown in Figure 4. The plot shows that, for a lift-to-drag ratio of 0.28, the Mode III retrograde region begins at 10 minutes and 1.1 seconds. This represents the earliest time of abort at which the spacecraft, after separation from the S-IVB stage, free falls with no burn and lands at a range of 3200 nautical miles from Cape Kennedy. Beyond this point, a Mode III retrograde maneuver may be performed. Figure 4 thus gives the amount of ΔV and the SPS burn time required to achieve a landing range of 3200 nautical miles. If the entry vehicle has a lift-to-drag ratio of 0.229, Figure 4 shows that the Mode III retrograde region begins at 10 minutes and 1.4 seconds ground elapsed time, or 0.3 second later than for a lift-to-drag ratio of 0.28. The entry portion of the Mode III aborts were flown full-lift (bank angle of zero degree) until a deceleration level of 0.2 g was reached. At this time, the vehicle rolled to a 55-degree bank angle and held this attitude until drogue chute deployment.

The maximum burn time of the SPS engine for the AAP-1 mission is shown on the plot in Figure 4 as 59 seconds. This corresponds to a ΔV of 1120 feet per second. Figure 4 shows that if the SPS burns to fuel depletion, the last time at which a Mode III retrograde abort could be performed for a lift-to-drag ratio of 0.229 is 10 minutes and 14.4 seconds ground elapsed time. For a lift-to-drag ratio of 0.28, the last Mode III retrograde abort capability occurs at 10 minutes and 14 seconds. If a flight propellant reserve of 10 percent (corresponding to a burn time of 5.9 seconds) is imposed on the mission, the end of the Mode III capability is reduced to 10 minutes and 13.3 seconds for a lift-to-drag ratio of 0.229, and to 10 minutes and 12.8 seconds for a lift-to-drag ratio of 0.28. Without the 10 percent flight propellant reserve, the Mode III retrograde abort region for both lift-to-drag ratios used in the study would extend slightly past insertion which occurs at a ground elapsed time of 10 minutes and 13.93 seconds.

Figure 5 illustrates the Mode III region for posigrade aborts to the Indian Ocean. This plot is similar to Figure 4 but gives the amount of burn time and the corresponding ΔV required by the vehicle to perform a posigrade abort so that the range at landing is 8200 nautical miles from Cape Kennedy. Again, the two lift-to-drag ratios of 0.28 and 0.229 were employed for the entry portion of the abort maneuver. However, in the case of posigrade aborts, Figure 5 illustrates that there is no discernible difference between posigrade ΔV requirements when varying the lift-to-drag ratio between 0.28 and 0.229. The sensitivity of the Mode III posigrade abort maneuver is such that a very small change in ΔV during a burn results in much larger changes in landing ranges. Therefore, the differences in the ΔV required to achieve an 8200 nautical mile landing range resulting from the change in lift-to-drag ratio are too small to be seen on the plot in Figure 5. The entry trajectory for posigrade abort maneuvers is a half-lift entry.

If the SPS burns to fuel depletion, the first point on the nominal trajectory at which a Mode III posigrade abort could be performed occurs at a ground elapsed time of 9 minutes and 58.9 seconds. Allowing for a 10 percent flight propellant reserve reduces the Mode III posigrade abort capability. Figure 5 shows that a 10 percent flight propellant reserve causes the first Mode III posigrade abort capability to occur at 10 minutes and 0.3 second. The last point on the nominal at which a Mode III posigrade abort need be performed is at a ground elapsed time of 10 minutes and 11.7 seconds. It is at this abort point that the spacecraft, after separation from the S-IVB, would free fall with no burn to a landing range of 8200 nautical miles using a half-lift entry. After this point in time on the nominal trajectory, some other action should be taken, such as a Mode IIIB retrograde to the Indian Ocean, to ensure a landing range of 8200 nautical miles.

Figure 6 diagrams the Mode IV abort region from the nominal trajectory. The figure points out that the first contingency orbital insertion capability using all the available propellant occurs at a ground elapsed time of 10 minutes and 0.2 second. If a 10 percent flight propellant reserve is placed on the maneuver, the Mode IV capability begins at a ground elapsed time of 10 minutes and 1.5 seconds. The 10 percent flight propellant reserve reduces the maximum ΔV capability of the SPS to 1000 feet per second. The Mode IV abort maneuver burn is terminated when the instantaneous predicted perigee altitude reaches 75 nautical miles. Since the nominal insertion orbit is an 81- by 120-nautical mile perigee to apogee altitude ratio, the Mode IV region terminates short of insertion at a ground elapsed time of 10 minutes and 12.6 seconds.

Figure 7 presents the off-nominal Mode IV abort capability in terms of flight-path angle at abort versus ground elapsed time at abort. Shown on the plot are Mode IV capability lines for constant values of ΔV. As an example, if an off-nominal abort occurred at a ground elapsed time of

10 minutes and 8.0 seconds with a flight-path angle at abort of 0.38 degree, a ΔV of 600 feet per second would be required to perform the Mode IV insertion into a 75-nautical mile perigee orbit. Constant ΔV lines are shown for zero, 300, 600, and 1000 feet per second. The 1000-foot per second ΔV line does not represent the full ΔV capability of the SPS engine, but is the maximum ΔV available after a 10 percent flight propellant reserve is imposed on the mission. An additional Mode IV boundary line is shown in Figure 7. This is the Mode IV boundary line defining the contingency orbital insertion region allowing sufficient ΔV to perform the insertion into a 75-nautical mile perigee orbit and retaining sufficient ΔV for deorbit. This Mode IV boundary line crosses the nominal trajectory at a ground elapsed time of 10 minutes and 2.5 seconds.

Figures 8 and 9 represent a summary of plots 2 through 7. Shown in Figure 8 are the ΔV requirements as a function of ground elapsed time for Mode III, posigrade and retrograde aborts, and Mode IV contingency orbit insertion. The Mode III ΔV requirements are shown for lift-to-drag ratios of 0.28 and 0.229. Figure 9 conveys some of the same information as Figure 8 but shows more clearly the beginning and end of the abort regions and the amount of overlap between the abort modes in terms of ground elapsed time. Figure 9 shows the time effects of changing the lift-to-drag ratio on the Mode III retrograde abort. The reduction of Mode III and Mode IV abort regions due to holding a 10 percent flight propellant reserve are also shown. The portion of the nominal trajectory during which the zero burn landing points fall between 3200 and 8200 nautical miles is also clearly illustrated in Figure 9. This portion of the nominal trajectory occurs between the times of 10 minutes and 1.1 seconds and 10 minutes and 11.7 seconds. These times correspond to the beginning of the Mode III retrograde abort region (lift-to-drag ratio equal to 0.28) and the end of the Mode III posigrade abort region. If an abort occurred between these two times on the nominal trajectory, and if the vehicle separated and an SPS malfunction occurred, the landing point would fall between 3200 and 8200 nautical miles. It should be noted that the span of time during which Mode III abort capability exists is a function of the type of entry (bank angle) used. Varying the bank angle during entry changes the times of the Mode III abort capability.

Figure 10 illustrates the nominal launch trajectory ground track from lift-off through insertion, followed by a portion of the first revolution. The point at which nominal insertion occurs is shown. The in-flight points at which the vehicle's sub-earth point lies at distances of 3200 and 8200 nautical miles from Cape Kennedy are shown.

Table I. Launch Vehicle Data

Event	g.e.t. (sec)	Weight (lb)	Thrust (lb)	Altitude* (ft)	Geodetic Latitude (deg)	Longitude (deg)	Inertial Velocity (fps)	Inertial Azimuth (deg)	Inertial Flight-Path Angle (deg)
Launch escape tower jettison	178.116	280,882.7	224,152.8	282,512.0	28.65 N	79.22 W	8,122.8	86.48	17.47
S-IVB mixture ratio shift	429.416	148,681.3	184,153.0	544,853.0	29.06 N	71.77 W	15,440.2	88.89	0.215
Orbital insertion	613.930	69,898.8	0.0	508,376.0	28.76 N	61.35 W	25,706.7	94.58	0.00

*Referenced to the Fischer ellipsoid earth model

Table II. Spacecraft Data

Weight	
At CSM/S-IVB separation (total)	36, 300 lbs
SPS propellant	3, 800 lbs
SM/RCS propellant	3, 032 lbs
At atmospheric entry (command module)	14, 266 lbs
Propulsion	
SPS thrust	20, 290 lbs
SPS weight flow	64. 38 lbs/sec
SM/RCS thrust (four thrusters)	398. 4 lbs
SM/RCS weight flow (four thrusters)	1. 44 lbs/sec

Command Module Aerodynamics for Hypersonic

Lift-to-Drag Ratios

a) L/D = 0. 28

Mach Number	Trim Angle of Attack (deg)	L/D
0. 4	167. 9	0. 267
0. 7	165. 5	0. 254
0. 9	162. 9	0. 285
1. 1	156. 6	0. 392
1. 2	156. 8	0. 387
1. 35	155. 5	0. 413
1. 65	154. 8	0. 412
2. 0	154. 8	0. 396
2. 4	155. 4	0. 385
3. 0	155. 8	0. 368
4. 0	157. 6	0. 342
Hypersonic	161. 4	0. 280

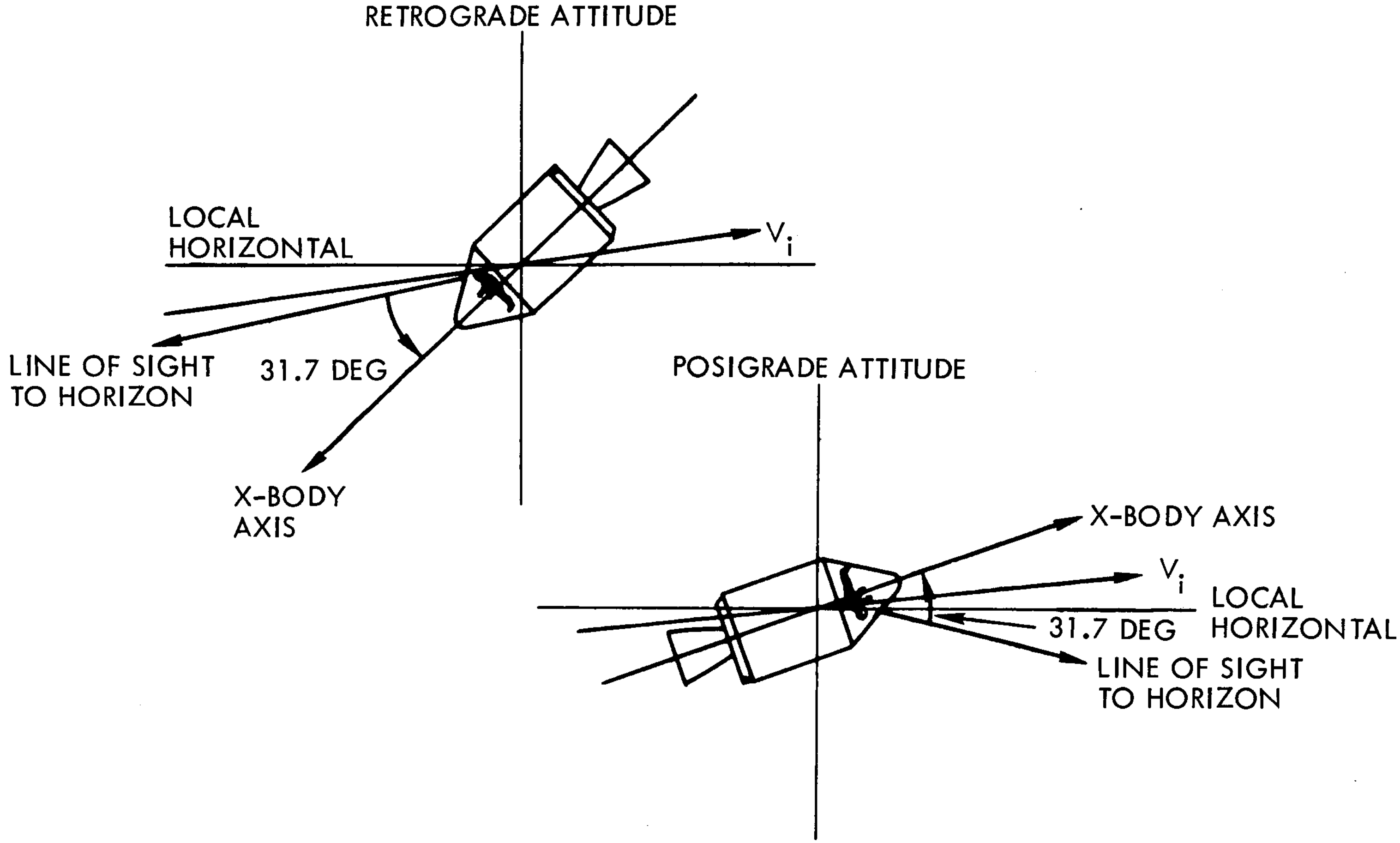
b) L/D = 0. 229

Mach Number	Trim Angle of Attack (deg)	L/D
0. 4	170. 08	0. 213
0. 7	168. 27	0. 221
0. 9	165. 87	0. 238
1. 1	161. 33	0. 310
1. 2	160. 9	0. 316
1. 35	159. 5	0. 343
1. 65	158. 6	0. 352
2. 0	158. 8	0. 342
2. 4	159. 3	0. 327
3. 0	160. 0	0. 306
4. 0	161. 0	0. 290
Hypersonic	164. 9	0. 229

Table III. Sequence of Events for Mode III and Mode IV Launch Aborts

Time from Launch Vehicle Shutdown (min:sec)	Event
	Mode III
0:00.00	Launch vehicle cutoff (abort signal)
0:01.85	End of S-IVB tailoff
0:03.00	Ullage (four jets) on
0:23.00	Begin SCS orientation maneuver to SPS ignition attitude
	(Mode III - retrograde and Mode IIIA - posigrade - RCS direct)
	Ullage off
2:05.00	SPS thrust on - SPS thrust off when: 1) Impact point = 3200 n mi (Mode III) 2) Impact point = 8200 n mi (Mode IIIA)
	Mode IV
0:00.00	Launch vehicle cutoff (abort signal)
0:01.85	End S-IVB tailoff
0:03.00	CSM/S-IVB separation, RCS direct ulllage (four jets) on
0:23.00	Begin SCS maneuver to posigrade attitude - RCS direct ullage off
1:50.00	RCS direct ullage on*
2:05.00	RCS direct ullage off, SPS thrust on - SPS thrust off when resulting $h_p \geq 75$ n mi

*Not simulated



NOTE: SPS RETROGRADE AND POSIGRADE MANEUVERS WERE INITIATED AT S-IVB CUTOFF PLUS 125 SECONDS. THE ATTITUDES PRESENTED ABOVE WERE THE SPACECRAFT ORIENTATIONS AT SPS IGNITION.

Figure 1. Spacecraft Attitude at SPS Ignition for Launch Abort Maneuvers

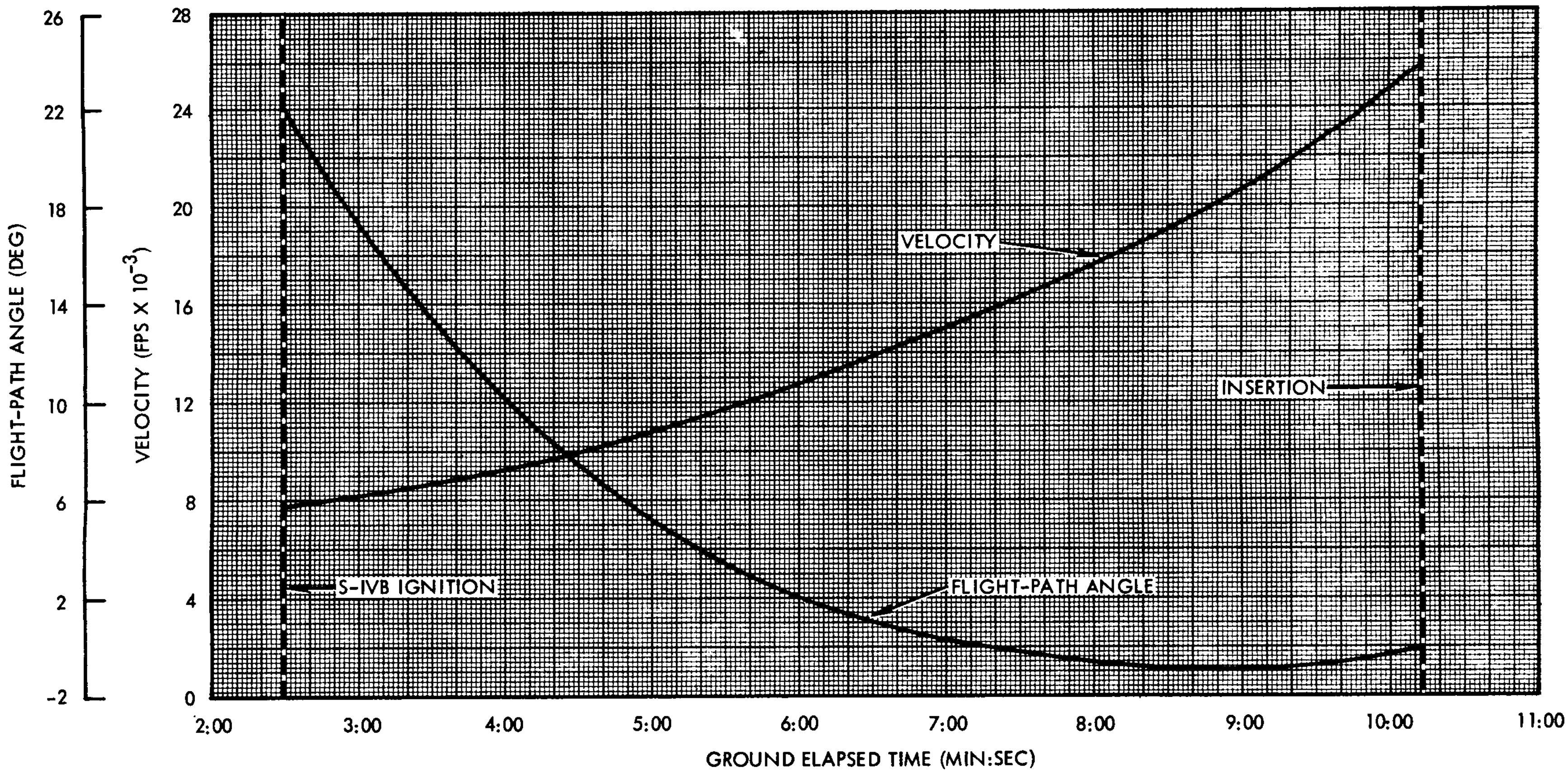


Figure 2. Inertial Flight-path Angle and Inertial Velocity as a Function of Ground Elapsed Time for the Nominal Launch Trajectory

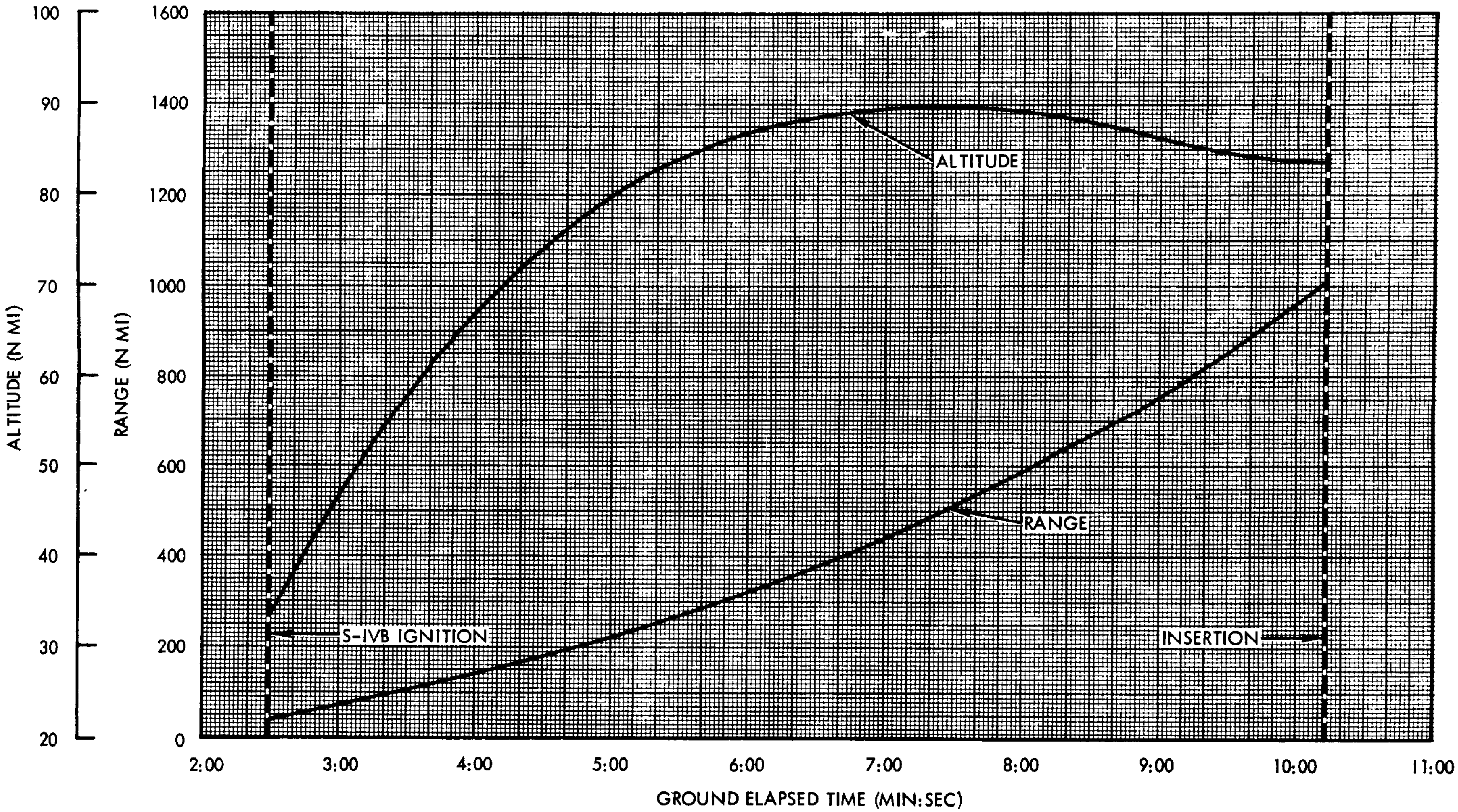


Figure 3. Altitude and Range as a Function of Ground Elapsed Time for the Nominal Launch Trajectory

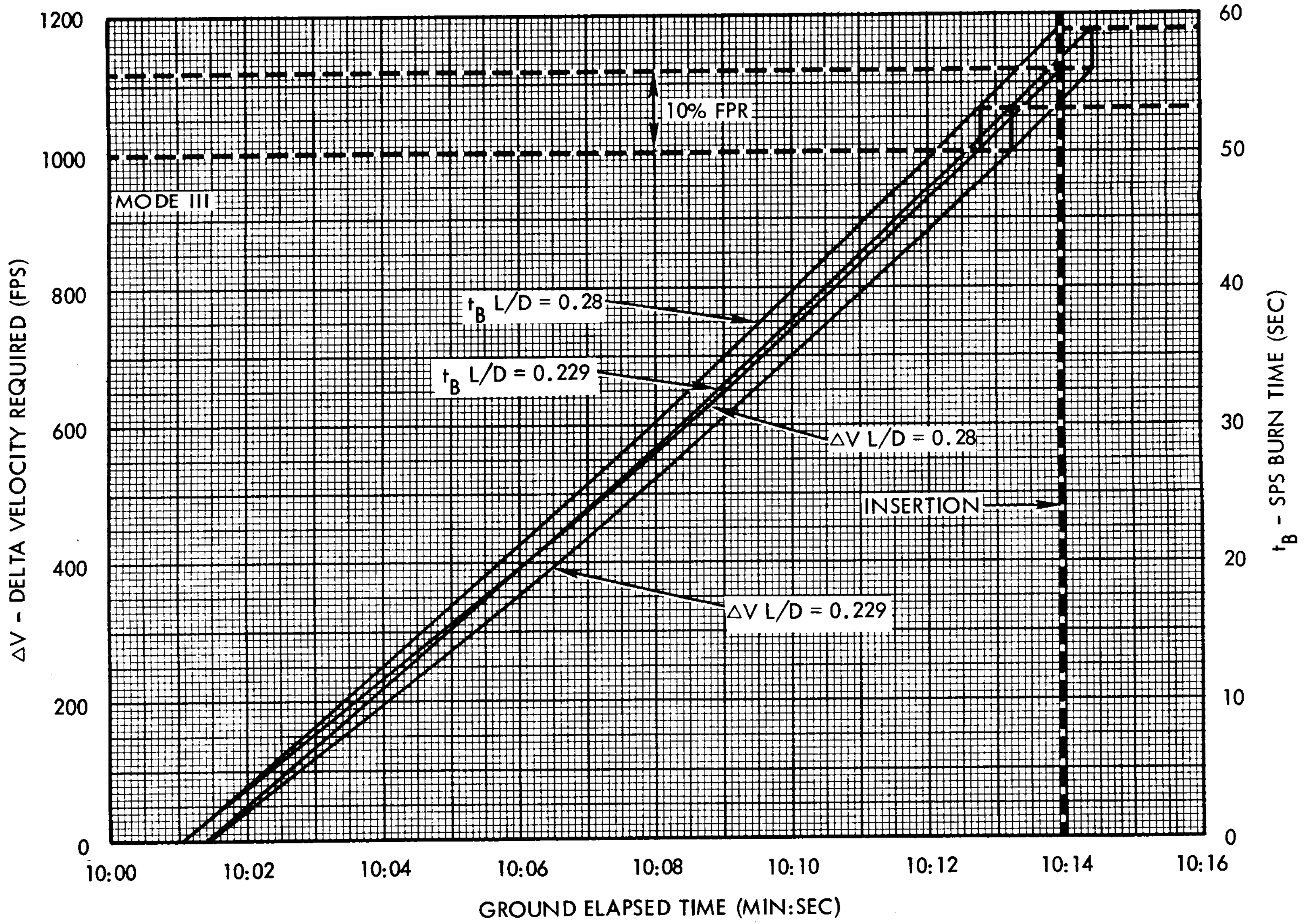


Figure 4. Mode III Delta Velocity and SPS Burn Time Required as a Function of Ground Elapsed Time - Atlantic Ocean Recovery Area

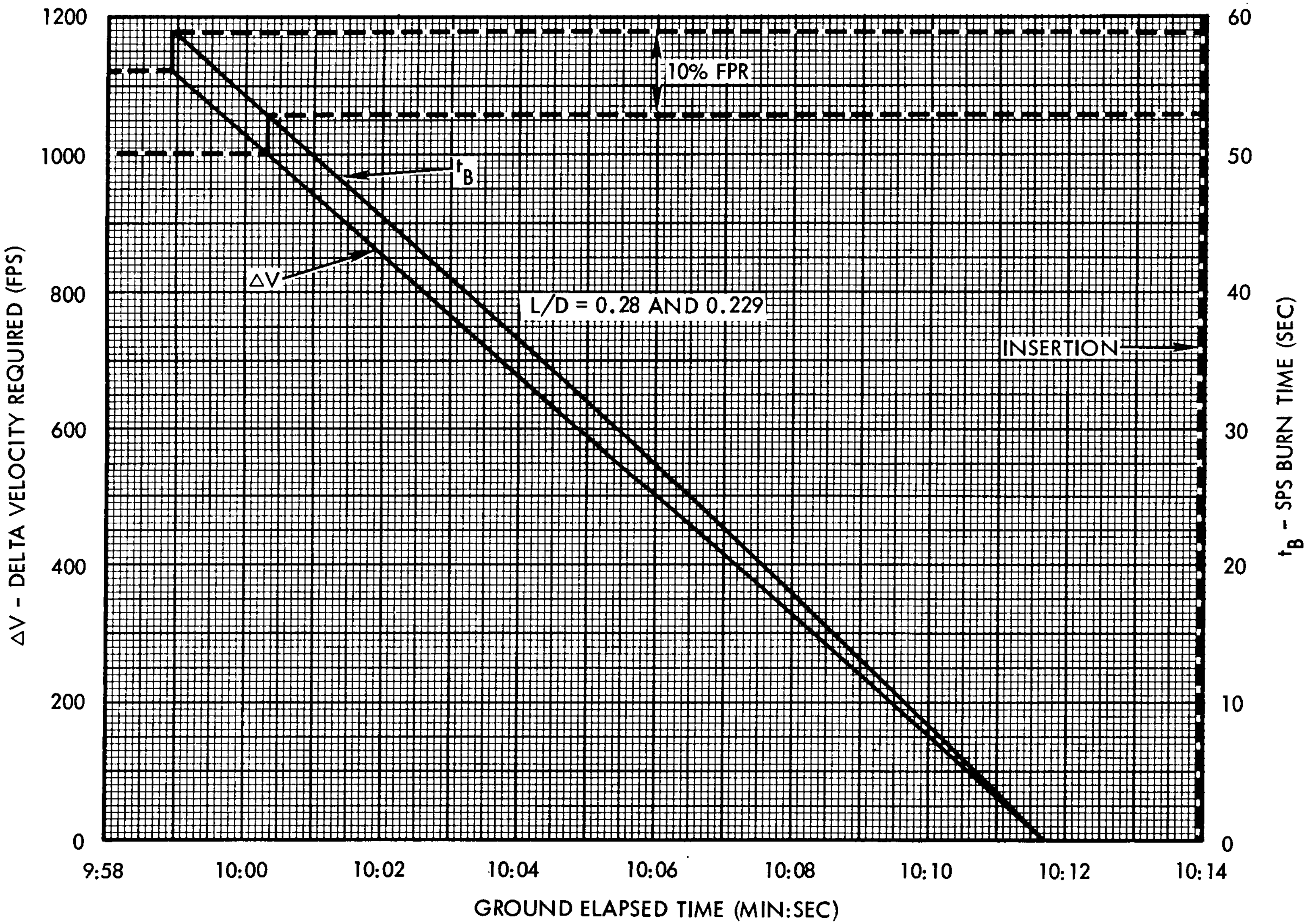


Figure 5. Mode III Delta Velocity and SPS Burn Time Required as a Function of Ground Elapsed Time - Indian Ocean Recovery Area

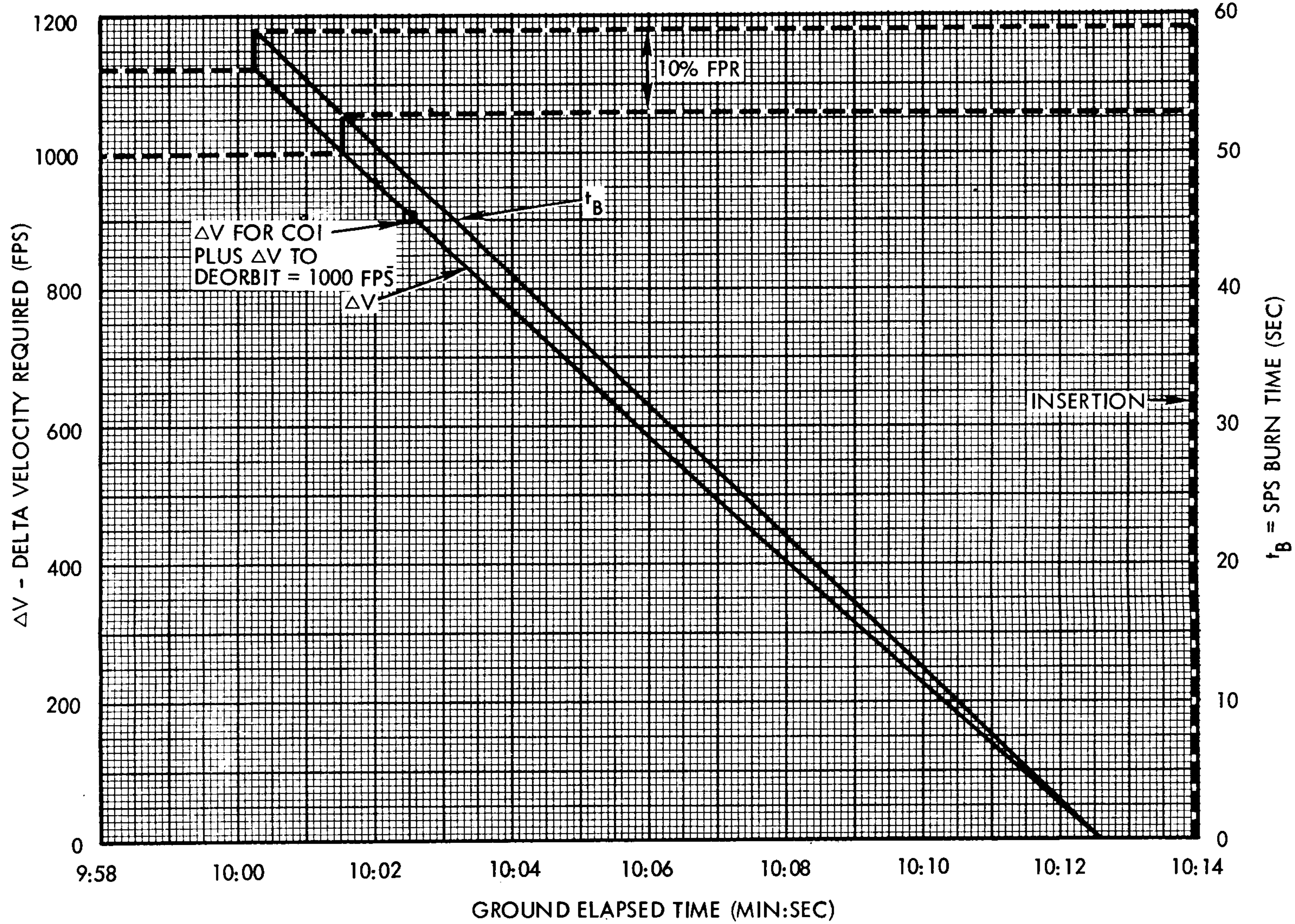


Figure 6. Mode IV Delta Velocity and SPS Burn Time Required as a Function of Ground Elapsed Time on the Nominal Launch Trajectory - Perigee Altitude at Insertion Equals 75 Nautical Miles

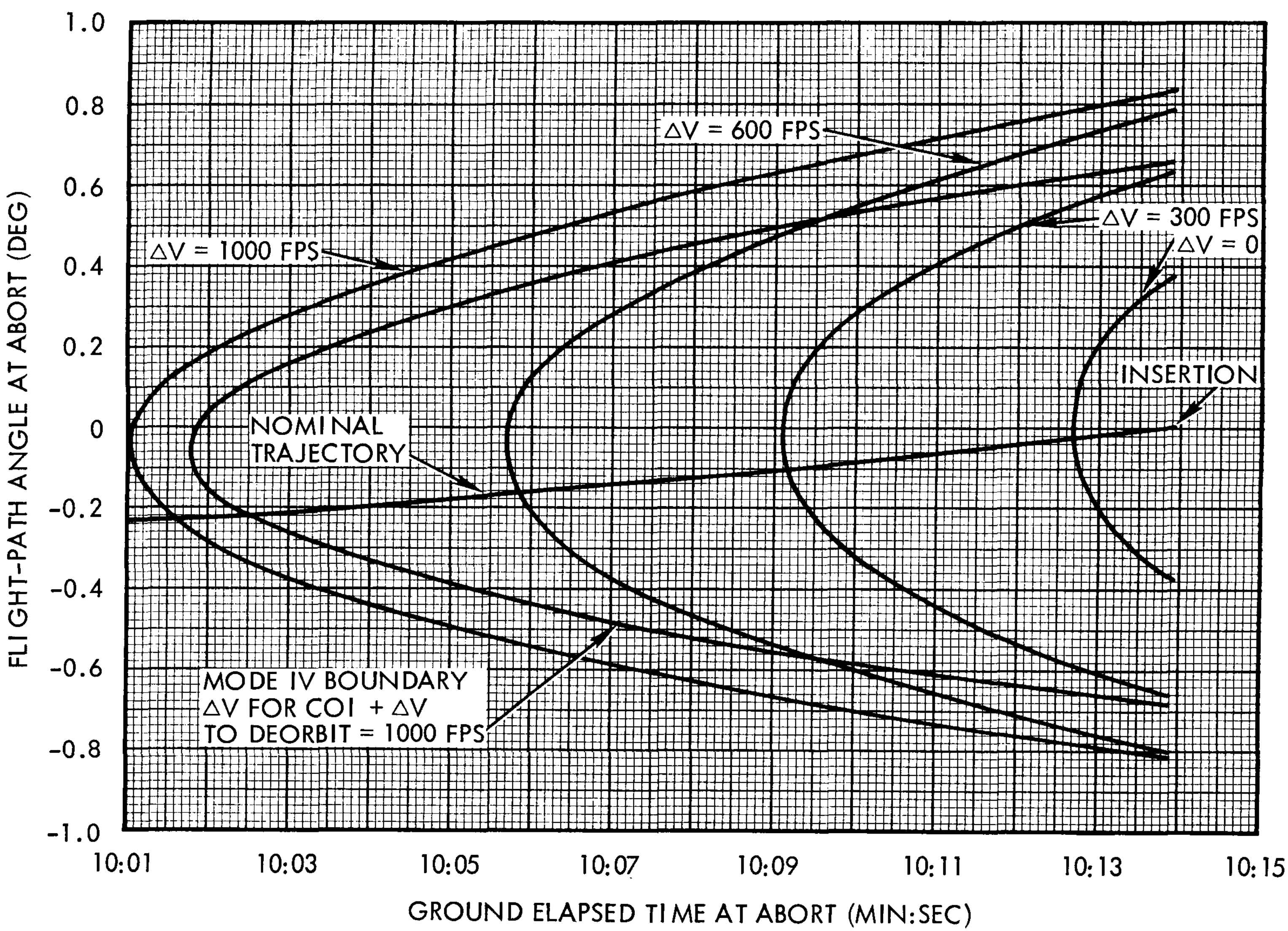


Figure 7. Mode IV Delta Velocity Required as a Function of Ground Elapsed Time for Off-nominal Cases - Perigee Altitude at Insertion Equals 75 Nautical Miles

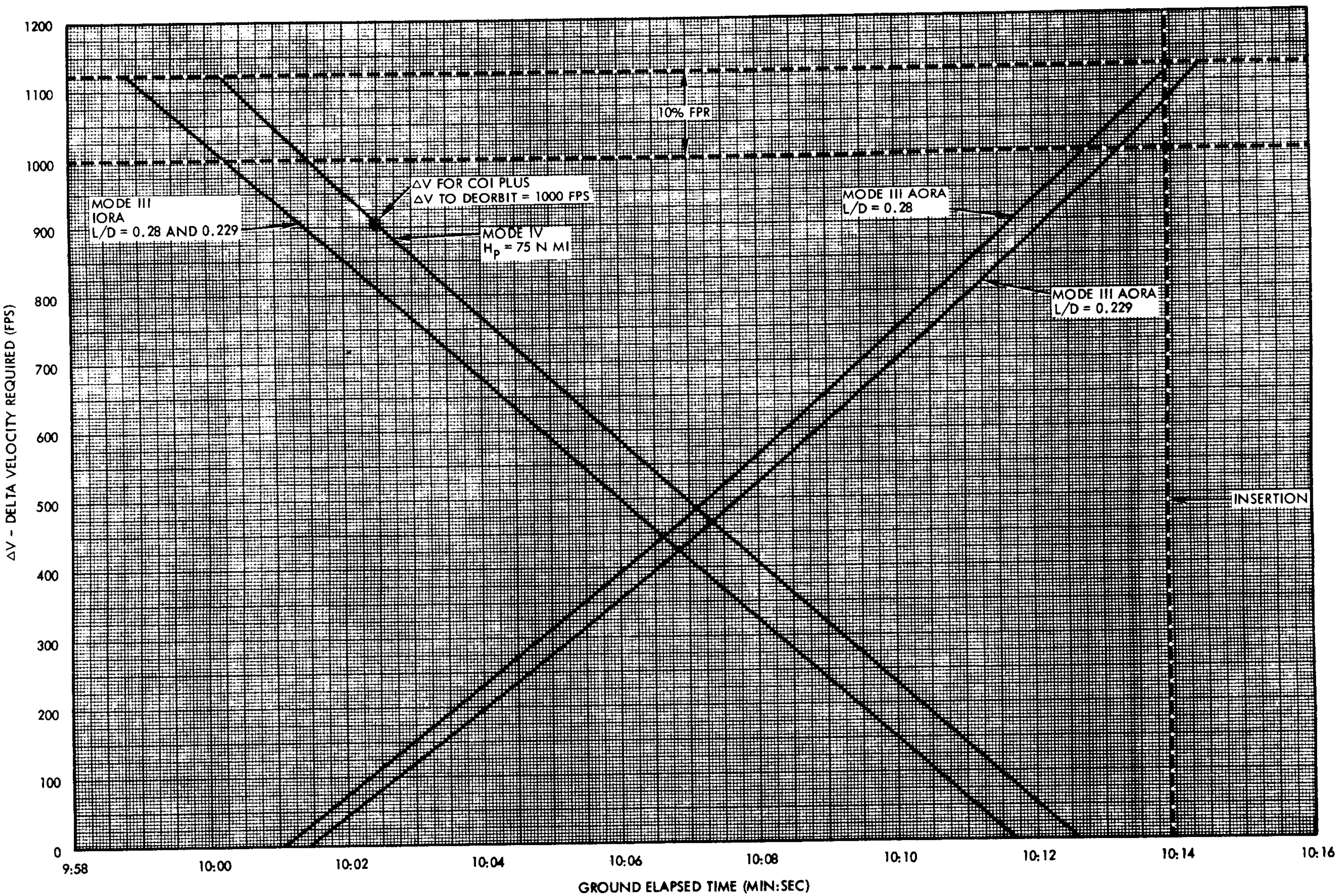


Figure 8. Mode III and Mode IV Delta Velocity Required as a Function of Ground Elapsed Time

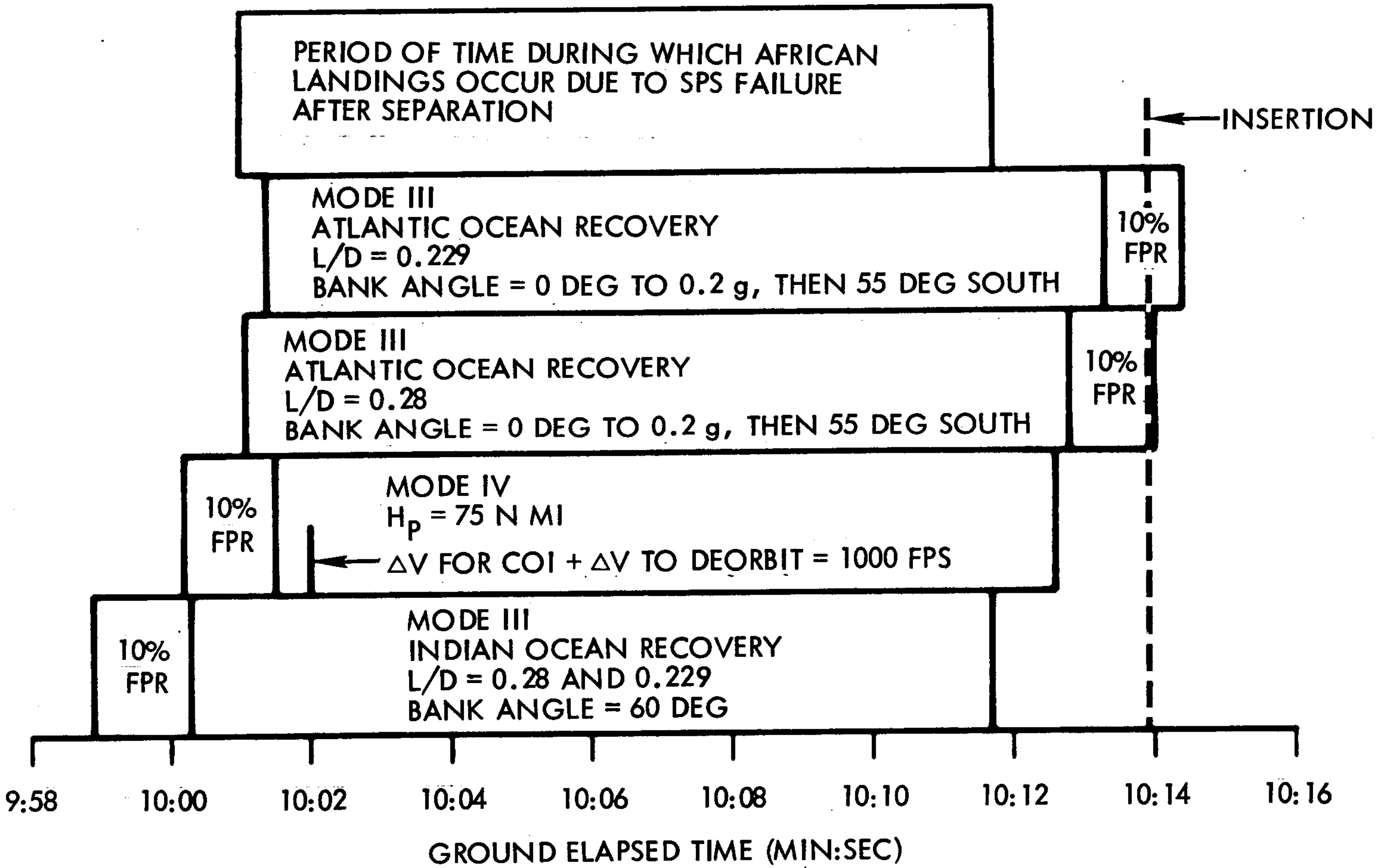


Figure 9. Mode III and Mode IV Summary Chart

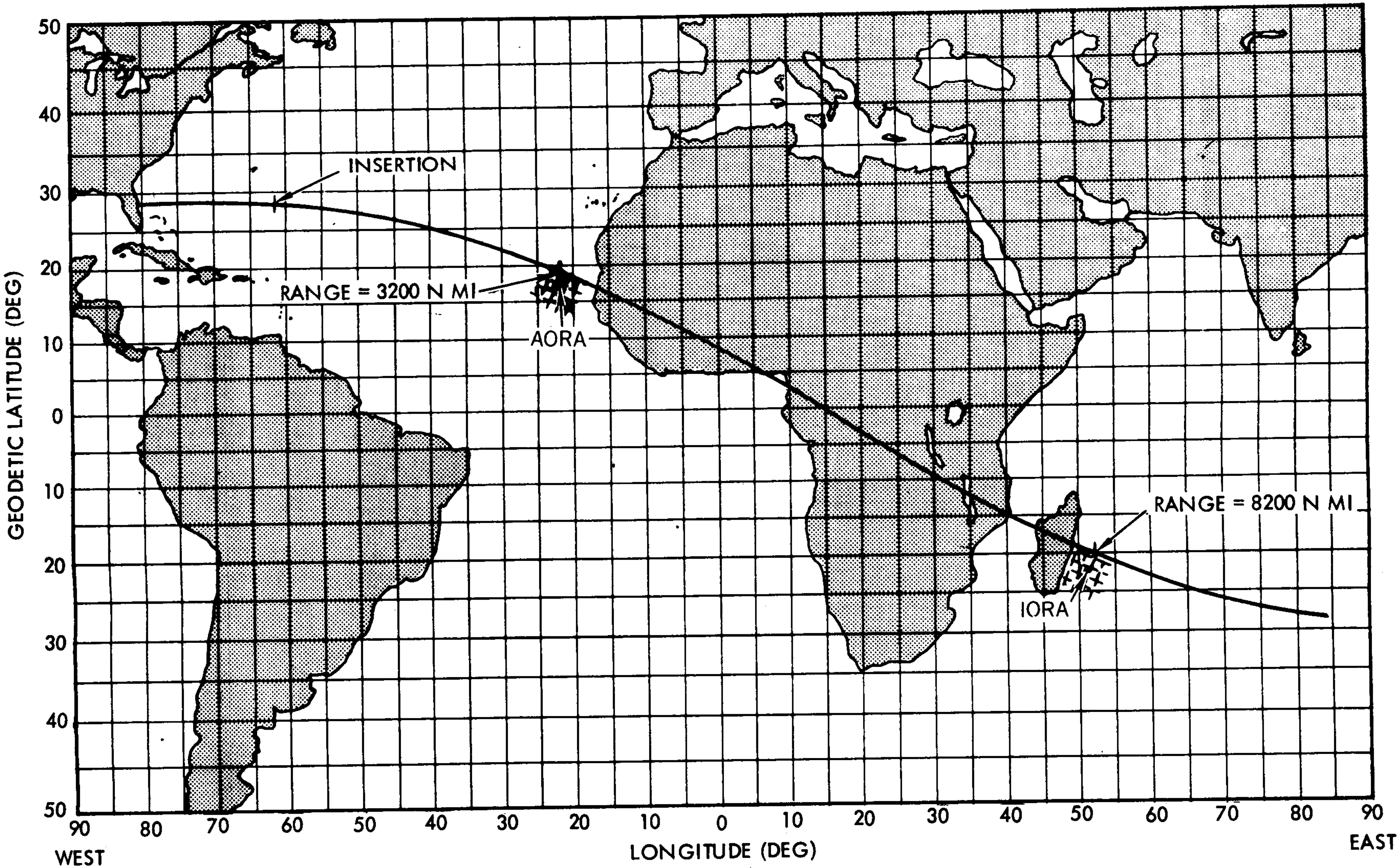


Figure 10. Ground Track for 28.9-Degree Inclination Orbit

REFERENCE

Toelle, R. G.: AAP-1 Preliminary Performance Data and Flight Profile. R-AERO-DAP-9-68, April 23, 1968.